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HEAT TRANSFER PROBLEMS IN ADVANCED GAS TURBINES FOR NAVAL APPLI--ETC(U)
AUG 77 E R ECKERT, R J GOLDSTEIN, E M SPARROW N00014-76-C-0246

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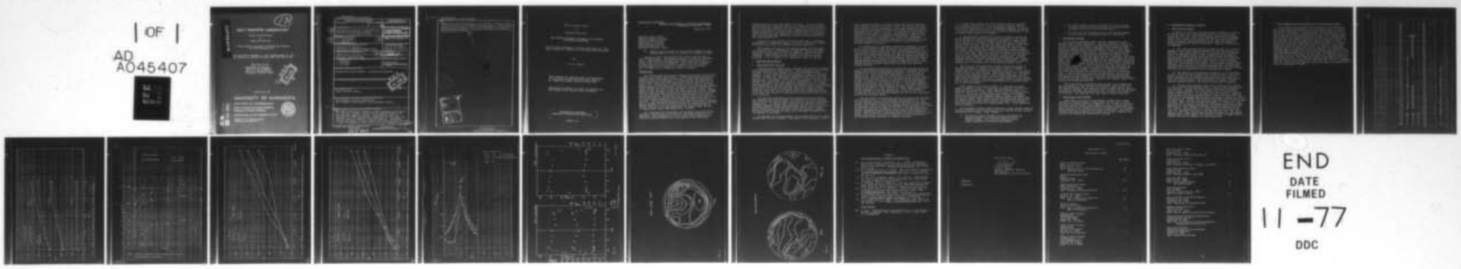

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HEAT TRANSFER LABORATORY

Annual Progress Report

of

Research concerning

"Heat Transfer Problems in Advanced Gas Turbines
for Naval Applications"

for the period September 1, 1976 through August 31, 1977
on Contract No. N00014-76-C-0246, Work Unit NR 097-383

Submitted to the

DEPARTMENT OF THE NAVY
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

August 30, 1977

UNIVERSITY OF MINNESOTA

INSTITUTE OF TECHNOLOGY

School of Mechanical and Aerospace Engineering
Department of Mechanical Engineering

MINNEAPOLIS, MINNESOTA 55455

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The report covers heat exchanger studies stressing measurements of local heat transfer coefficients by a method based on the heat and mass transfer analogy. Local ablation rates are obtained on a model covered with napthalene and from these heat transfer rates are deduced through the analogy. Impingement cooling and porous wall heat transfer have also been investigated. A number of studies in film cooling were also completed: over

(over)

165 400

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Experiments covered measurements in a cascade, effects of free stream conditions and of laminar boundary layer. A laser-Doppler setup was used to measure local and instantaneous velocities at the exit cross-section of a gas turbine combustor and turbulence intensities were derived.

Annual Progress Report

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for the period September 1, 1976 through August 31, 1977
under contract No. N00014-76-C-0246, Work Unit NR 097-383

by

E. R. G. Eckert

This research was conducted under the sponsorship of the Office of Naval Research under Contract No. N00014-76-C-0246, Work Unit NR 097-383.

UNIVERSITY OF MINNESOTA
Department of Mechanical Engineering

August 1977

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Minneapolis, Minnesota 55455

August 30, 1977

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Re: Annual progress report for the period September 1, 1976 through August 31, 1977 on contract No. N00014-76-C-0246.

During the above mentioned period, work was carried out in four research phases. The progress obtained in those is discussed below. Publications and theses which have resulted from this research are listed in the Appendix. Copies have been forwarded to your office or will be mailed as soon as they are available. The following faculty members are involved in this research: E. R. G. Eckert, R. J. Goldstein, and E. M. Sparrow.

INTRODUCTION

Our research during the above mentioned period has been directed to marine gas turbine applications. Closed cycle plants promise to achieve higher efficiency and therefore a reduced fuel consumption - especially when heat exchangers are inserted into the power cycle. On the other hand, these heat exchangers increase the weight of the plant and it is important to reduce their size as much as possible. Compact types of heat exchangers which have been developed by industry have minimized the surface area required to transfer a prescribed amount of heat and have in this way reduced size and weight. Various shapes of heat transfer surfaces have been developed for this purpose. This has been done empirically and the individual surfaces have not yet been optimized. One phase of our research effort is directed toward this goal by accurate and local measurements which will result in a basic understanding of the flow and heat transfer processes involved. The work performed during this reporting period is actually part of a major systematic study which has been described by Professor Ephriam Sparrow in an invited lecture which he presented when he became recipient of the Max Jakob Award (E. Sparrow,"Heat Transfer in Complex Duct Flows" ASME publication 77-HT-95).

The efficiency of closed cycle gas turbines, as of all thermal engines, increases with an increase of the highest temperature in the cycle. This temperature is on the other hand limited by the materials used and cooling has to be applied to the structural

elements exposed to the high temperature gases. In closed cycle gas turbines this situation occurs in the heat exchanger in which energy created by combustion or nuclear fission is transferred to the gas performing the closed cycle. Impingement cooling is especially effective for the local cooling of hot spots. A research phase has therefore been devoted to a study of the basic flow and heat transfer processes associated with this cooling method with the aim to optimize it.

Research on film cooling of turbine blades and on turbulence measurements in combustion chambers which had already been started in previous years has been continued towards completion.

The progress obtained in the research phases mentioned above is discussed below. Publications and theses which have resulted from this research are listed in the Appendix. Copies have been forwarded to your office or will be mailed as soon as they are available. The following faculty members are involved in this research: E. R. G. Eckert, R. J. Goldstein, and E. M. Sparrow.

A. HEAT EXCHANGER STUDIES

1. Interrupted Wall Passages

High-performance compact heat exchangers are frequently designed using interrupted-wall flow passages. Heat exchangers based on this principle are used, for example, in Navy closed Brayton cycle engines. In the application of this concept, the walls of the heat exchanger passages are interrupted periodically along the direction of flow. In this way, the overall length of a flow passage is subdivided into a succession of very short flow passages. Since a short passage has a much higher heat transfer effectiveness than a long passage, the use of the interrupted-wall concept leads to a significant improvement of the heat transfer performance of the heat exchanger. On the other hand, the interruptions give rise to higher pressure drops and to an increase in the power required to pump the fluid. Therefore, both heat transfer and pressure drop considerations have to be taken into account in evaluating the total performance of such heat exchangers.

The available literature on heat exchangers with interrupted-wall passages is concerned almost exclusively with overall performance tests on full scale devices, each with its specific geometrical configuration. It appears that a detailed and systematic study of processes internal to such heat exchangers has yet to be carried out. An understanding of these processes would enable a more rational choice of the geometrical and flow parameters involved in design. The experimental program now under way is intended to provide basic information of this type.

In carrying out the experiments, use is being made of the analogy between heat and mass transfer. According to this principle, infor-

mation obtained from mass transfer experiments can be applied to heat transfer situations, and vice versa. On the basis of extensive experience in our laboratory, it has been demonstrated that mass transfer experiments can serve as a highly efficient tool for determining heat transfer results. The particular mass transfer technique which appears to be most advantageous in modeling heat transfer to air flows is naphthalene sublimation. Compared with direct heat transfer experiments, the use of the naphthalene technique enables more accurate measurement of the transfer rates, is less susceptible to extraneous losses, and provides better-defined boundary conditions.

To illustrate the naphthalene sublimation technique, consider an air stream passing along the surface of a naphthalene plate. At the plate surface, solid naphthalene sublimes into vapor and is carried away by the flowing air. The rate of sublimation is controlled by the difference between the concentration of naphthalene vapor at the surface and the concentration of naphthalene vapor in the air stream. The ratio of the sublimation rate to this concentration difference is termed the mass transfer coefficient. The experimentally determined mass transfer coefficients can be transformed into heat transfer coefficients by using the heat/mass transfer analogy.

An experimental facility has been designed and constructed to employ the naphthalene sublimation technique in studying the transfer processes in an interrupted-wall passage. The heart of the apparatus is a flat rectangular duct with a 5:1 cross-sectional aspect ratio. The portion of the duct which serves as the test section is designed so that one of the walls can be readily removed to facilitate the installation or removal of naphthalene-coated plates. A schematic side view of the duct with the naphthalene-coated plate in place is pictured in Fig. 1. The figure shows the geometric parameters which influence the heat transfer characteristics of the plates. These include the plate length L, the plate-to-plate spacing S, and the thickness t. These three parameters can be combined to form the dimensionless ratios S/L and t/L. In addition to these geometrical groups, the flow rate is parameterized via the Reynolds number.

The experiments performed to date have focused on the two-plate system shown in Fig. 1, with additional plates planned for later. For the two-plate system, heat transfer coefficients (i.e., mass transfer coefficients) have been measured for duct Reynolds numbers ranging from 2,000 to 25,000, for spacing ratios S/L from 0 to 2, and for thickness ratios t/L from 0.04 to 0.12. The thickness ratio studies are especially noteworthy because the current trend toward greater compactness gives rise to larger values of the thickness ratio. This is because the thickness cannot be made smaller than the minimum required for structural integrity, so that t/L increases as the plate length decreases at constant thickness.

Pressure drop studies are now in progress and are expected to be completed before the end of the present contract period. The pressure drop results are not sufficiently complete to warrant their being reported here, but it is definitely planned to include the pressure drop along with the heat transfer coefficients in any subsequent publication of the results.

A representative selection of the heat transfer results will now be presented in order to illustrate the nature of the trends, and attention will first be turned to the effects of plate thickness. In Fig. 2, the Nusselt number is plotted as a function of the thickness ratio t/L for the case where the spacing S and plate length L are the same. Results are shown both for the first plate and the second plate at Reynolds numbers of 4,000, 15,000, and 25,000. The figure shows that at the higher Reynolds numbers, there is a definite increase in the Nusselt number with thickness. For the first plate, this increase is on the order of fifty percent, while for the second plate the increase is about thirty percent. These are major effects and have design implications. At lower Reynolds numbers, the plate thickness has a lesser effect, especially for the first plate. This trend can be attributed to viscous damping that is characteristic of low Reynolds number flows.

The effect of the separation distance between the plates on the Nusselt number is shown in Fig. 3 for a range of Reynolds numbers and for the intermediate thickness ratio t/L = 0.08. The results span the range from zero separation distance to a separation which is twice the plate length. Not unexpectedly, the first plate is very little affected by the extent of the separation. On the other hand, the Nusselt number for the second plate decreases markedly at small spacings. The results indicate that S/L should exceed 0.5 in order to attain the full augmentation of the Nusselt number due to the interruption.

The response of the Nusselt number to increases Reynolds number is shown in Figs. 4(a) and 4(b), respectively for the first plate and the second plate. These figures include results for thickness ratios t/L = 0.04, 0.08, and 0.12, for the spacing ratio S/L = 1. For all of the thicknesses investigated, the Nusselt number increases with the Reynolds number. However, it appears that thicker plates show a stronger Reynolds number dependence than do thinner plates. This finding can be rationalized by noting that the thicker plates bring forth a variety of fluid flow phenomena which are quite sensitive to Reynolds number (e.g., flow separation, vortex shedding).

The foregoing results, which constitute a representative sampling of the information generated during the grant period, permit certain conclusions to be drawn. These include:

1. Increases of plate thickness can be responsible for marked increases in the Nusselt number at higher Reynolds number. The effect of thickness is of lesser significane at low Reynolds numbers.

2. The plate-to-plate spacing should be at least one-half the plate length in order to attain the maximum possible increase of the heat transfer coefficient.

3. The increase of the Nusselt number with Reynolds number is more rapid for thick plates than for thin plates.

2. Impingement Cooling

The study on impingement heat transfer progressed in two different but related experiments. The first study is aimed at a detailed look at heat transfer to a bounding wall from a single air jet in a crossflow of varying magnitude. This study will help provide an understanding of the fundamental nature of local flow conditions and local heat transfer. Figure 5 shows, as an example, local heat transfer coefficients at the surface on which the jet impinges at different dimensionless distances x/D measured from the centerline of the tube from which the jet is ejected. One curve holds for no crossflow and the other one for a small amount of crossflow. The injection Reynolds number and the dimensionless distance, L/D from the exit plane of the tube to the heat transfer surface are also noted in the figure together with M, the mass flux ratio of the jet to the crossflow. It can be observed that with crossflow the heat transfer distribution is shifted in downstream direction and that the peak heat transfer coefficient is diminished somewhat. The amount of crossflow for the data in the figure is relatively weak. A larger amount of crossflow accentuates the shift of the peak as well as the diminution of the heat transfer coefficient. Previously reported studies were concerned with similar phenomena, but we are now able to maintain a constant jet Reynolds number while varying the freestream velocity.

The second study investigates heat transfer with multiple air jets impinging on a flat surface for different arrays of the jets. The spacing between the jet exit holes and the heat transfer plate will also be changed. The crossflow will be produced by the gas from neighboring jets located upstream and will therefore vary along the test section. The apparatus for this study is almost completed.

3. Porous Wall Heat Transfer

Experiments have also been performed to study heat transfer between air flowing through a porous plate and the plate surface. The study has essentially been completed. We are able to correlate the heat transfer results using simple relations by separating the heat transfer to the surface area on the approach side of the porous plate from that to the surface internal to the plate. The results of this study can be applied to a number of systems including full surface film cooling and transpiration cooling.

B. COMPLETION OF WORK IN PROGRESS

1. Film Cooling Studies

A number of studies in film cooling were brought to fruition during the past year. They include studies on the effects of a) cascade flow, b) freestream conditions (especially turbulence level) and c) laminar flow in the mainstream and in the injected fluid. Three papers were presented at the 1977 Tokyo Joint Gas Turbine Congress, organized jointly by the ASME and Japanese Engineering Societies and held last fall. Copies of these papers are appended.

a. The study on film cooling of turbine blades in a cascade demonstrates the importance of curvature to the film cooling performance. Experiments showed that the film cooling effectiveness may be considerably better or worse, depending on the relative values of the momentum flux ratio and the relative densities of the injected and the mainstream fluids on a convex or concave film cooled surface as compared to a flat surface. Observed trends could also be predicted analytically. The curvature effects have important ramifications to the design of film-cooled turbine blades and demonstrate that the assumption generally used in calculating boundary layer development on curved surfaces that only the velocity variation in the mainstream has to be considered is wrong.

b. The importance of turbulence parameters in the mainstream on film cooling has been demonstrated in our research. The turbulence intensity and the boundary layer thickness were found to affect particularly the lateral spreading of the film cooling jets over the cooled surfaces. This influences the optimum spacing between injection holes in the design of film cooling systems.

c. Previous film cooling studies were concerned with systems in which the mainstream boundary layer, as well as the injected jet, are turbulent. During the present reporting period film cooling with a laminar boundary layer and laminar flow of the jets were studied experimentally. It was found that the laminar or turbulent characteristic of the mainstream boundary layer does not affect the film cooling performance significantly, although it affects the flow structure in the neighborhood of the mixing region between the jet and the mainstream. However, the turbulence characteristic of the injected jet does affect the film cooling performance in a major way. The penetration of a laminar jet into the mainstream is greater and this decreases the film cooling performance in the vicinity of the injection region. This finding is at least partially explained by the fact that the momentum flux of a laminar tube flow is larger than that of a turbulent tube flow at the same blowing rate. The larger momentum flux causes greater penetration and lowers the film cooling effectiveness. This study in the form of a thesis is close to completion and will be prepared for publication soon.

2. Laser-Doppler Velocity Measurements in Combustion Systems

This project has progressed well following the installation of a 6-inch gas turbine burner and a new optical bench to isolate the optical components from the vibration generated by the burner and the air flow system. New oscillators for the Bragg cells were made using printed circuit boards and the oscillators power supply and RF amplifiers were combined into a single unit. Measurements of local and instantaneous velocities in hot and cold flows through the combustor are almost completed. The distributions of time mean velocity and time averaged fluctuating velocity u' as well as temperature along the radial distance from the center of the combustor cross-section are shown in Fig. 6. Figures 7 and 8 show isotherms and mean velocity as well as time-averaged fluctuating velocity contours within the exit cross-section. One observes that the turbulence intensity has a value of approximately 40% in the cold flow and approximately 20% in the hot flow. The difference is probably due to the acceleration of the gas when it expands during the combustion process. The turbulent kinetic energy remains about the same in the hot flow as in the corresponding cold flow and it appears that the influence of combustion on the turbulence level is negligible. More runs have been made with the system up to peak gas temperatures in the neighborhood of 1080°C.

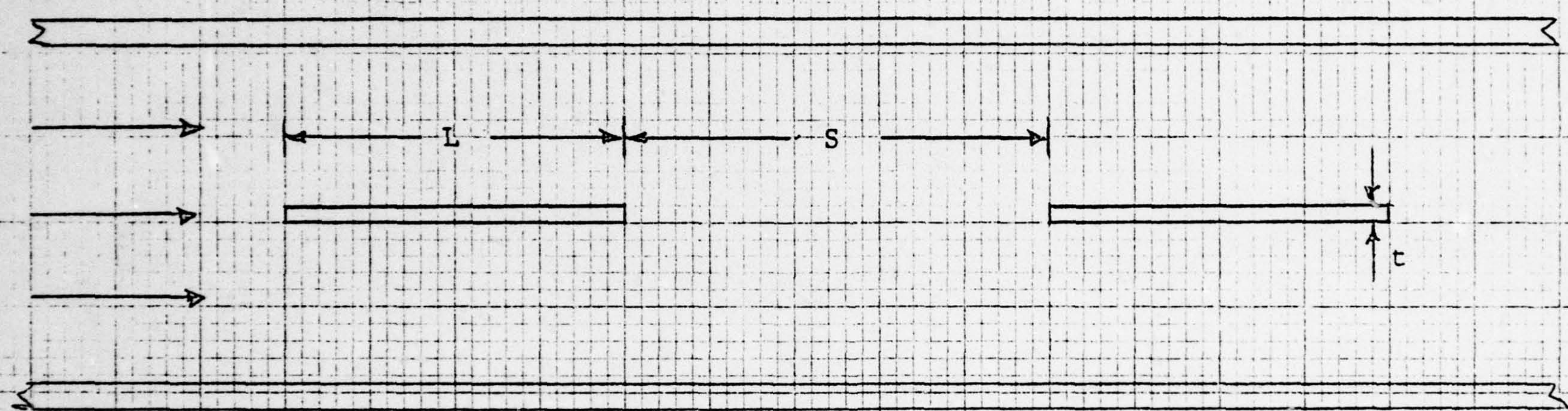


Fig. 1 Schematic diagram of the experimental set-up

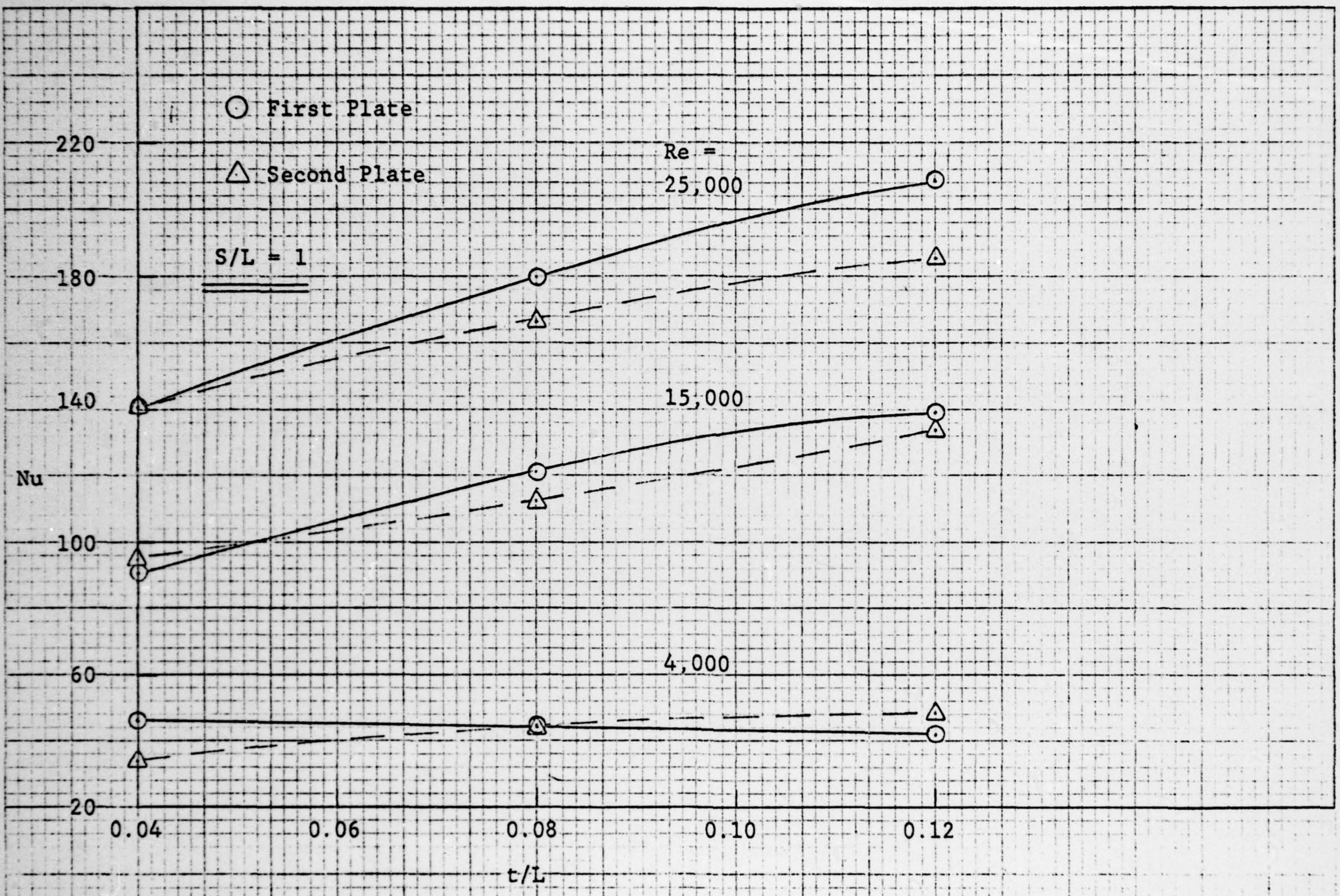


Fig.2 Effect of plate thickness on the heat transfer performance

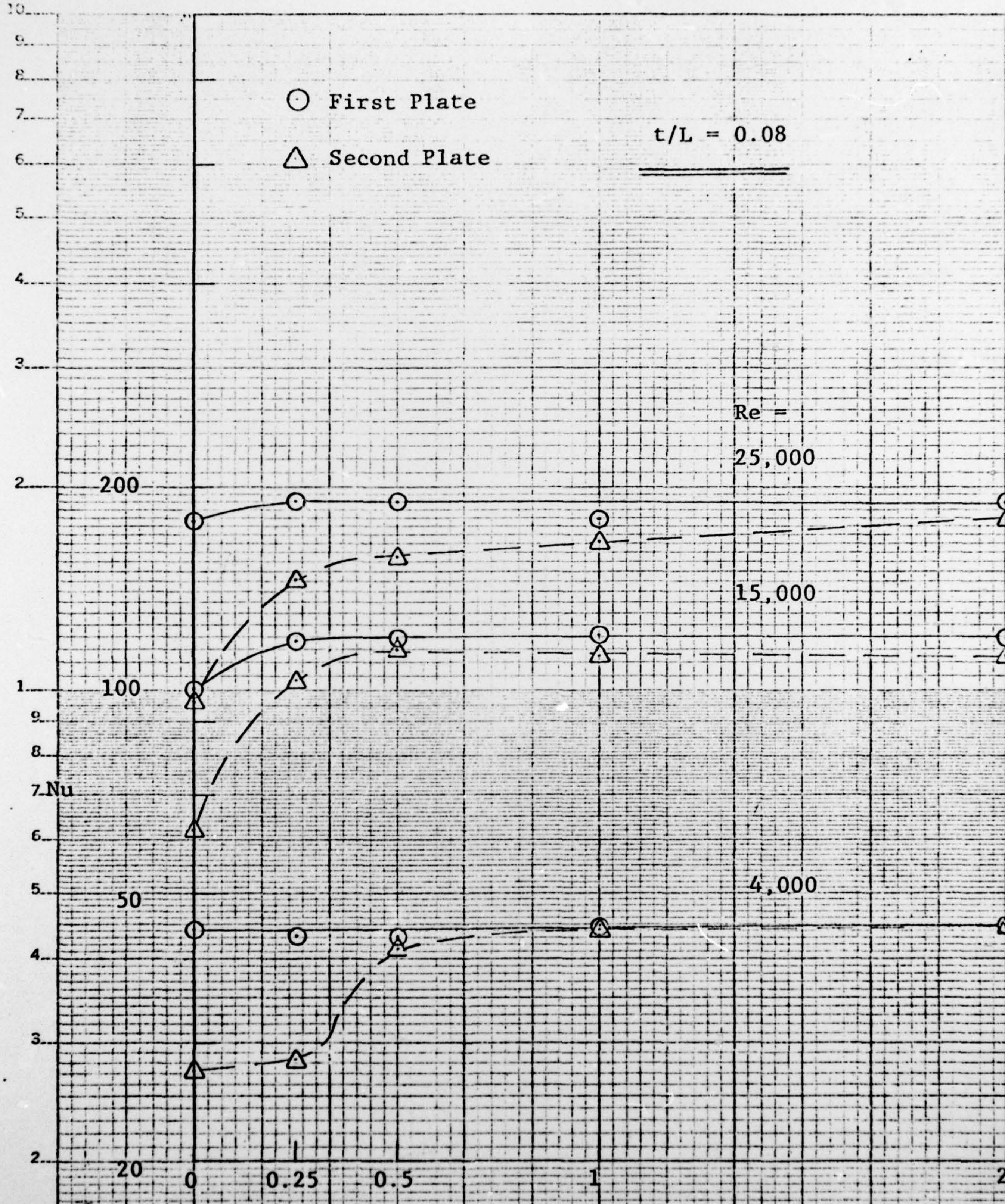


Fig.3 Effect of plate-to-plate separation on the heat transfer performance

Semi-Logarithmic
2 Cycles x 10 to the inch

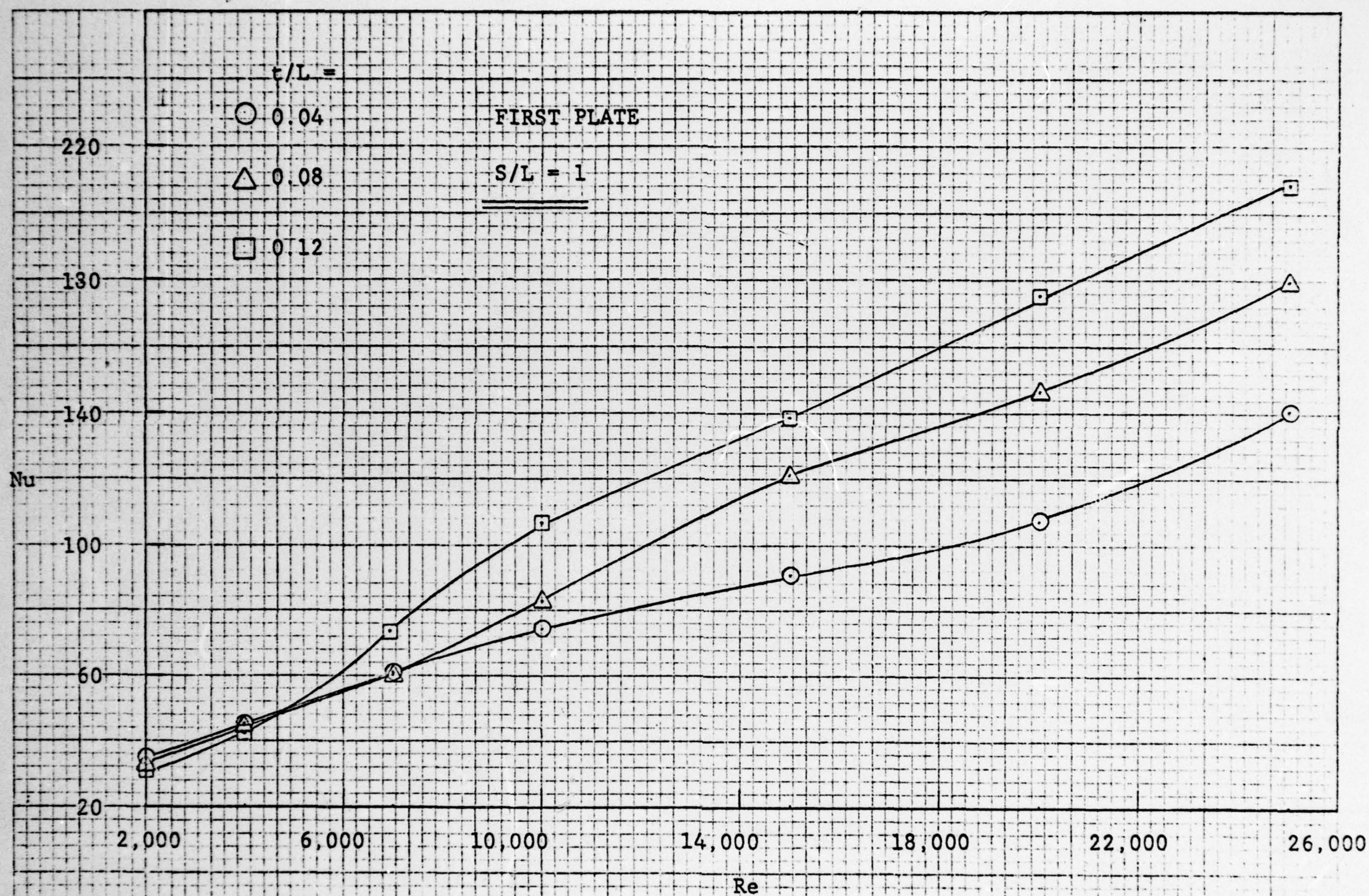


Fig. 4(a) Effect of Reynolds number on the heat transfer performance of the first plate

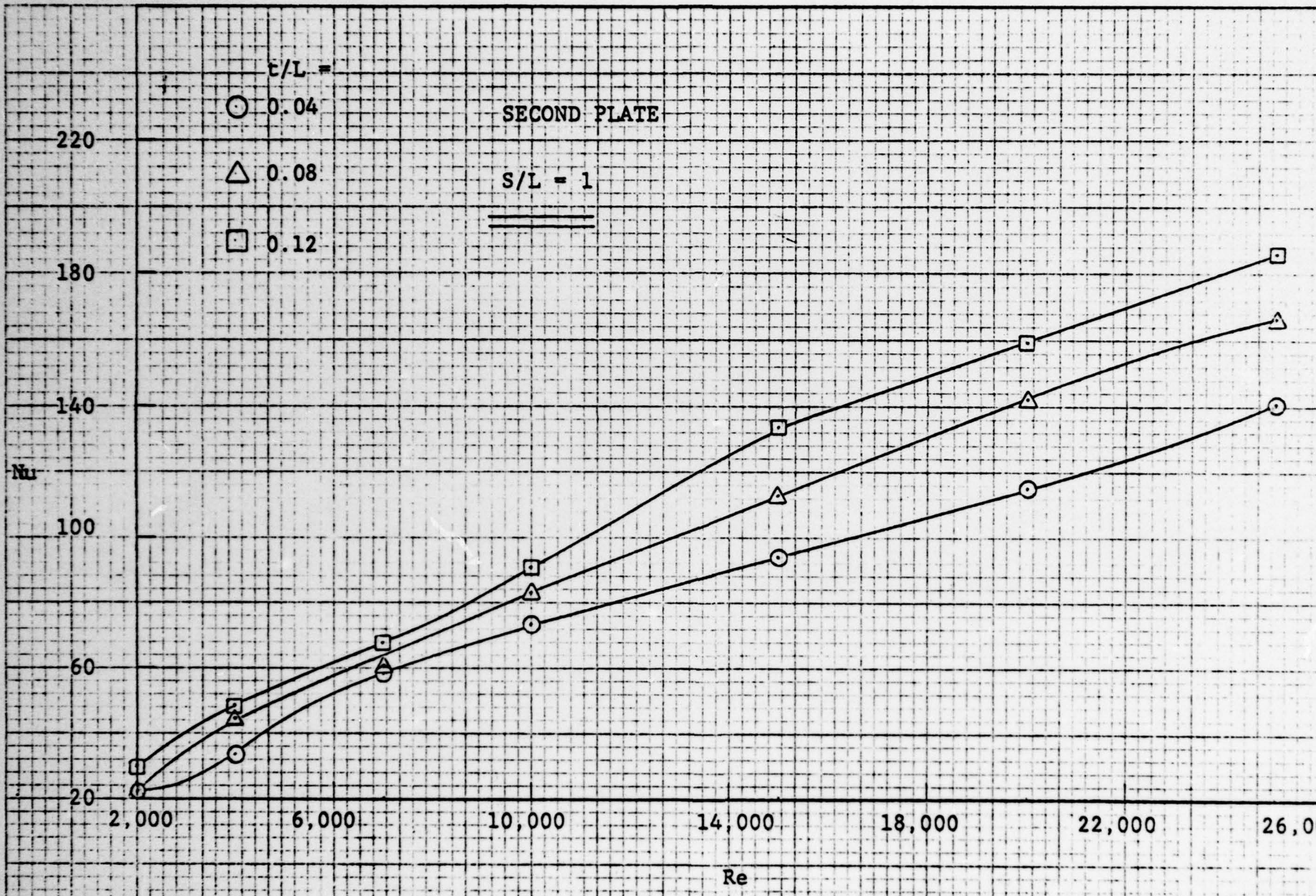
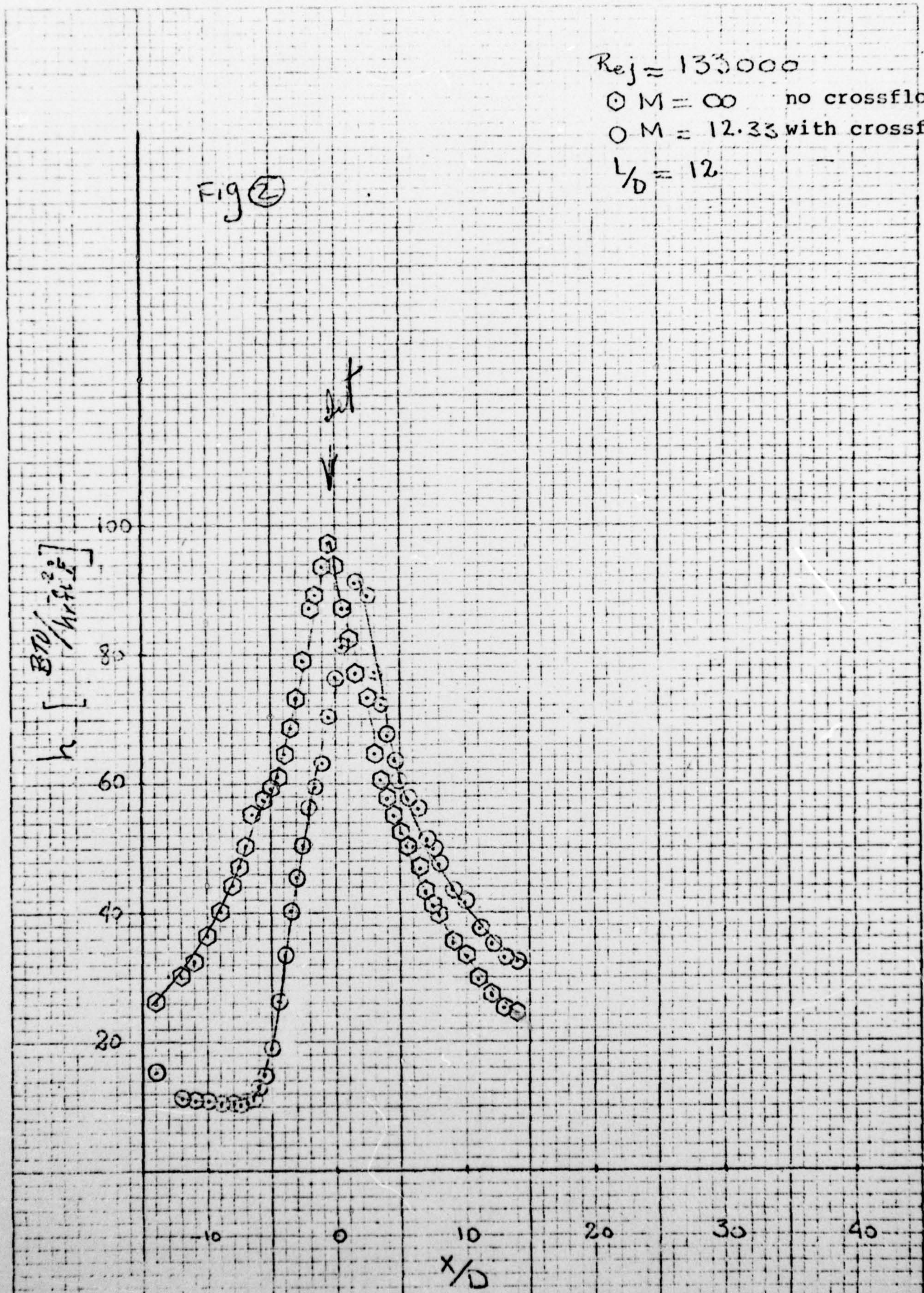


Fig. 4(b) Effect of Reynolds number on the heat transfer performance of the second plate



Rej = 133000
⊙ M = ∞ no crossflow
O M = 12.33 with crossflow
L/D = 12
Fig 2
Jet
h [BTU/hr ft² °F]
100
80
60
40
20
-10
0
10
20
30
40
X/D

Fig. 5

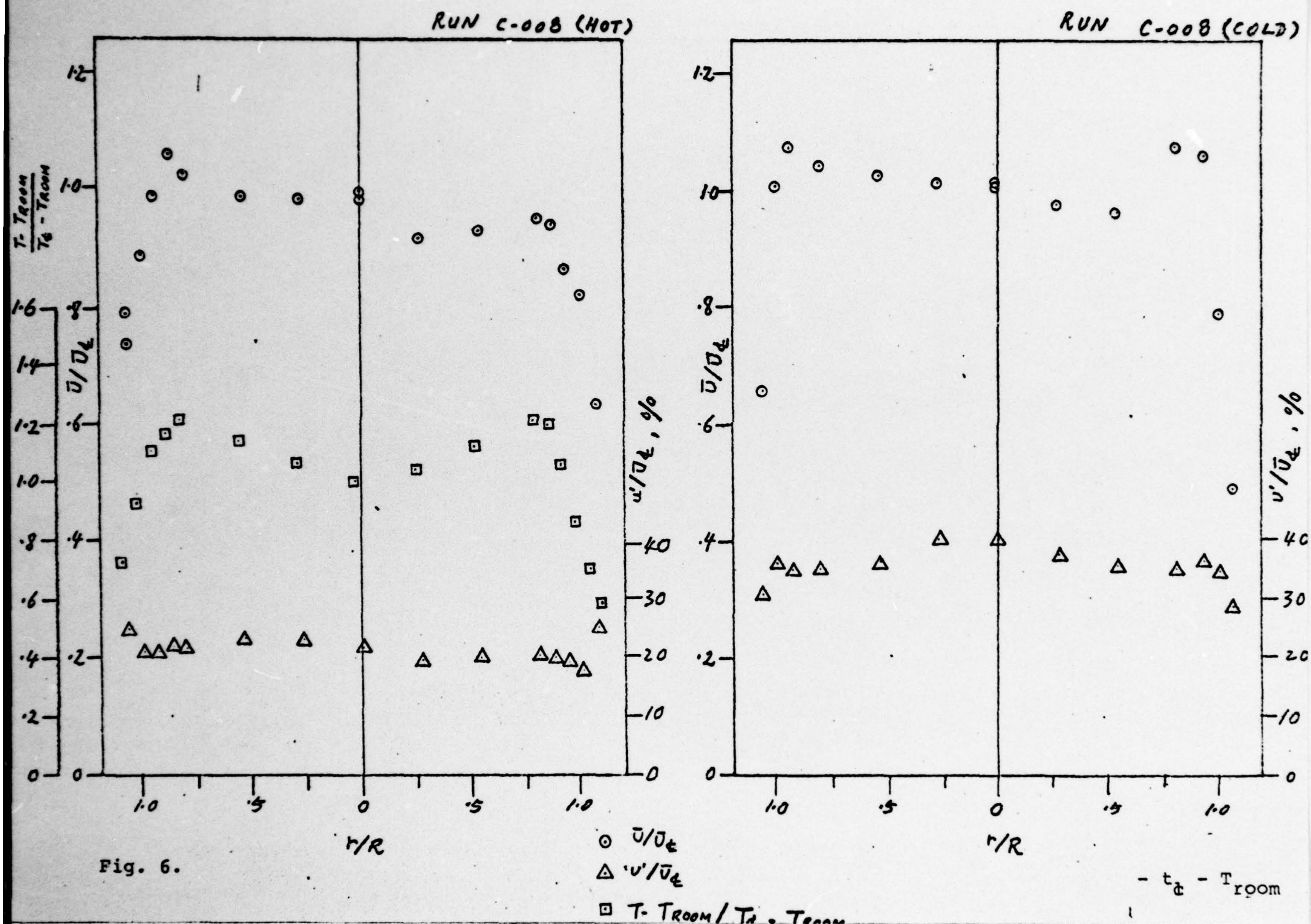
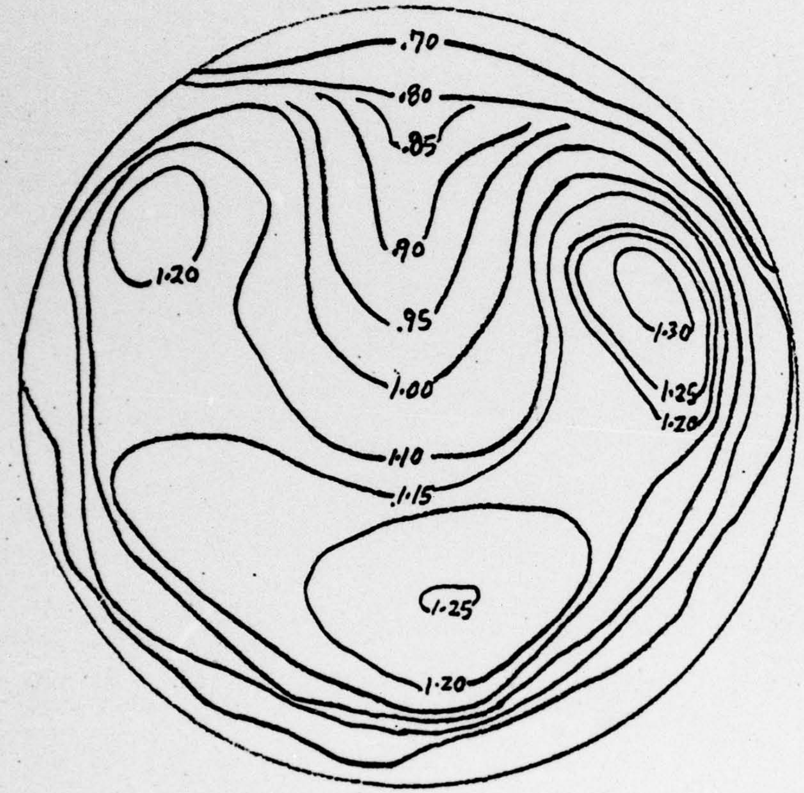


Fig. 6.

$- t_{\mathfrak{C}} - T_{room}$

RUN C-005 (HOT)



T/T$_E$

Fig. 7.

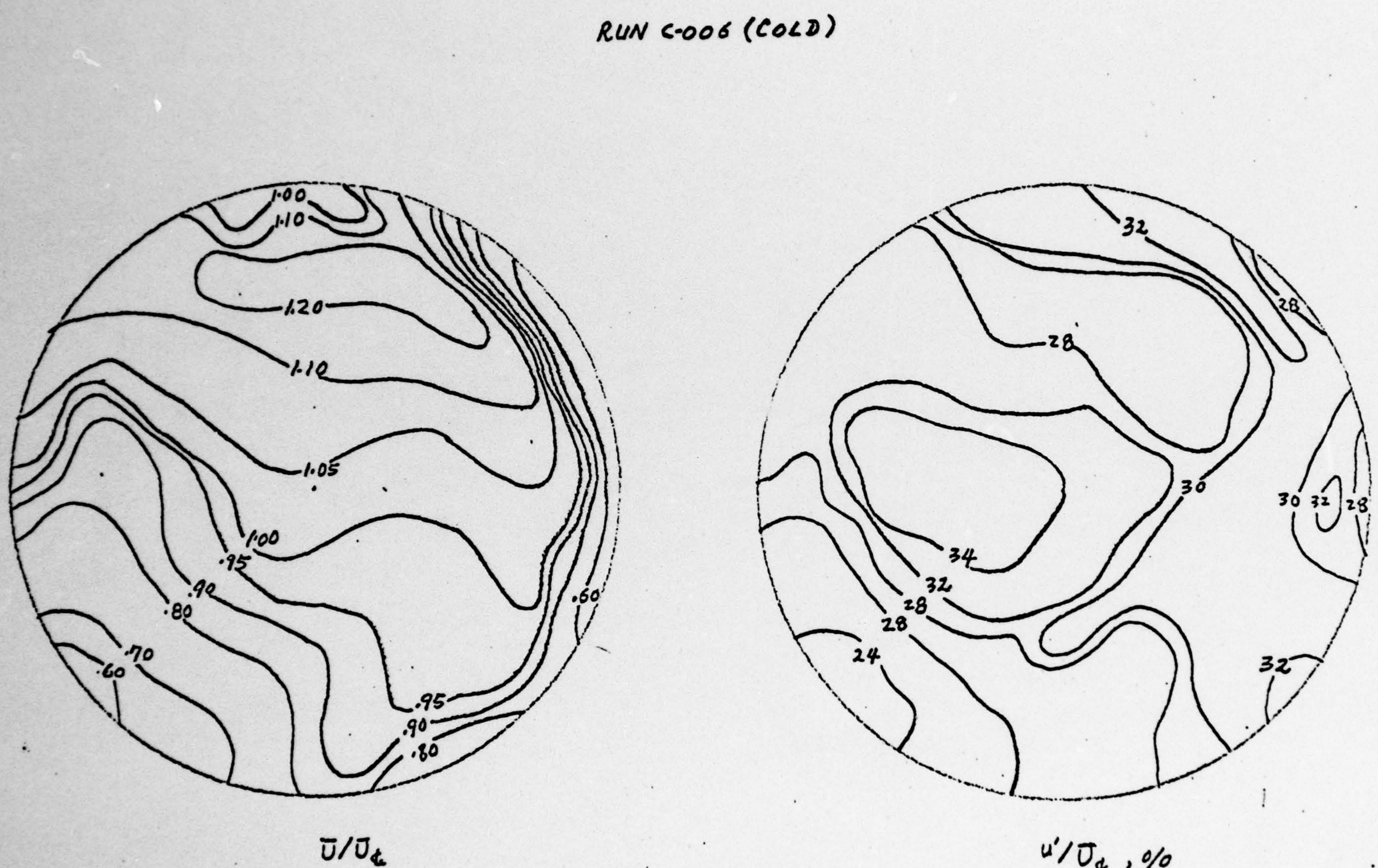

RUN C-006 (COLD)
1.00
1.10
1.20
1.10
1.05
1.00
.95
.90
.80
.70
.60
.95
.90
.80
.60
$\overline{U}/\overline{U}_{\mathbb{C}}$
32
28
28
30
30 32 28
34
32
28
28
24
32
$u'/\overline{U}_{\mathbb{C}}$, %

Fig. 8.

APPENDIX

Papers published or accepted for publication

1.) E. M. Sparrow and L. Goldstein, Jr.: "Effect of Rotation and Coolant Throughflow on the Heat Transfer and Temperature Field in an Enclosure," Journal of Heat Transfer, 98, (1976), pp. 387-394.
2.) R. J. Goldstein and D. K. Kreid: "The Laser-Doppler Anemometer," in Measurements in Heat Transfer, edited by E. R. G. Eckert and R. J. Goldstein, Hemisphere Publ. Corp., Washington, 1976, pp. 541-578.
3.) S. Ito, R. J. Goldstein, and E. R. G. Eckert: "Film Cooling of a Gas Turbine Blade," ASME publication, 1977 Tokyo Joint Gas Turbine Congress, paper No. 03.
4.) K. Kadotani and R. J. Goldstein: "On the Nature of Jets Entering a Turbulent Flow," parts A and B, ASME publication, 1977 Tokyo Joint Gas Turbine Congress, paper No. 05-A and 05-B.
5.) D. J. Wilson and R. J. Goldstein: "Turbulent Wall Jets with Cylindrical Streamwise Surface Curvature." Trans. ASME, J. Fluids Engineering, 98, (1976), pp. 550-557.
6.) M. Y. Jabbari and R. J. Goldstein: "Adiabatic Wall Temperature and Heat Transfer Downstream of Injection Through Two Rows of Holes," Trans. ASME, J. Engr. for Power, No. 77-GT-50.
7.) C. J. Scott and D. R. Rask: "Free Turbulent Shear Layers on Plug Nozzles," Trans. ASME, J. Fluids Engineering, 99, (1977), pp. 301-310.

Ph.D. Thesis:

8.) S. Ito: "Film Cooling and Aerodynamic Loss in a Gas Turbine Cascade,: December, 1976 (Advisors: E. R. G. Eckert and R. J. Goldstein)

Very truly yours,

E. R. G. Eckert
Regents' Professor emeritus
and Director
Thermodynamics and Heat Transfer

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